Estimate of X-Ray Shielding Required for Safe Operation of HINS RF Cavities in the Linac Enclosure in the Meson Detector Building

Bob Webber

January 20, 2009

Introduction

The Fermilab High Intensity Neutrino Source (HINS) R&D program will construct a shielding enclosure for the HINS 30 MeV linac in the Meson Detector Building (MDB). The linac comprises a Radio Frequency Quadrupole (RFQ), two copper-plated steel re-buncher RF cavities, sixteen copper (room temperature) RF accelerating cavities and eighteen β=0.2 SSR1 superconducting (SC) spoke resonator cavities. This note presents an estimate of the x-ray shielding required for full gradient operation of these cavities in the enclosure. Shielding requirement estimates for radiation due to the accelerated particle beam shall be documented elsewhere.

Assumptions and Estimates

This document proceeds along the lines of logic used in Beams-doc 2598-v3, "Estimate of X-Ray Shielding and Radiation Monitoring for Safe Operation of the HINS Cavity Test Cave in the Meson Detector Building".

This document does not consider x-rays produced in the RFQ. The RFQ is located outside the linac shielding enclosure and its construction includes a thick-wall steel vacuum vessel that provides attenuation for x-rays generated within the RF structure. X-ray measurements shall be made as the RFQ is commissioned to full RF power. Any required x-ray mitigations will be based on those measurements.

Estimates of x-ray yields are based on the maximum energy obtained by electrons emitted from the cavity surfaces, the number of electrons available, the power available to drive the electron current, and any physical factors that otherwise limit the electron current.

Electron Beam Energy Assumptions

All cavities to be operated in the HINS linac enclosure at MDB are all designed for acceleration of non-relativistic particles (e.g. β=0.2 for the SSR1 superconducting cavities). They are inherently ineffective for imparting the full, integrated multi-gap cavity voltage to particles of the "wrong" velocity. It is reasonable to assume that the maximum possible energy imparted to an electron in the system is that from just one accelerating gap in a single cavity rather than the sum of multiple gaps. Table 1 shows the parameters used for x-ray shielding calculation purposes for each of the relevant cavity types.

Table 1. Cavity Parameters

Cavity Type	Maximum Total Voltage	# of Gaps	Assumed Electron Beam Energy
Re-bunchers	0.165 MV	1	0.165 MeV
Copper 3-spoke	0.33 MV	2 full and 2 half	0.11 MeV
Copper 4-spoke	1 MV	3 full and 2 half	0.25 MeV
SC β=0.2	1.5 MV	2	0.75 MeV

Available Electrons

For purposes of shielding calculations, it is assumed that the number of available electrons is not a limiting factor.

Available RF Power

The HINS linac RF power distribution system is designed to supply a specific, individual level of power to each cavity determined by the cavity construction and the accelerator physics design of the linac. Tables 2 and 3 show the RF power required by each of the 16 copper cavities and the 18 superconducting cavities respectively. (Note that copper cavities 1-4 are the 3-spoke type and 5-16 are 4-spoke type.) The re-buncher cavities each require 6 kW RF power, well below that of the cavities that dominate the shielding requirements. The re-bunchers are considered no further.

The copper cavity table presents power requirements assuming 10 mA beam current, whereas the superconducting cavity table assumes 25 mA. For calculations in this document, the highest RF power level requirement for each cavity type is assumed, the copper cavity power is scaled up to that required for 25 mA beam current, and a 50% allowance for power overhead is applied. The assumed available operational power levels are then:

1.5*(10 + 25/10 * 2.14) = 15.4 kW for a Copper 3-spoke
1.5*(44 + 25/10 * 7.8) = 63 kW for a Copper 4-spoke
1.5*(32) = 48 kW for a superconducting β=0.2 cavity

A single 325 MHz, 2.5 MW peak power, pulsed klystron capable of a maximum 4.5 msec pulse and 1.5% duty factor drives the RF distribution system. Therefore, the time-averaged power available to any cavity is 1.5% that shown above. This gives:

231 W for a Copper 3-spoke
945 W for a Copper 4-spoke
720 W for a superconducting β=0.2 cavity

Table 2. Copper Cavity Power Requirements*

2. Power consumption in the room temperature CH cavities.

Cavity number	design type	β geom.	β particle	Rsh MOhm	Veff MV	φ_s deg	dW MeV	W MeV	P_{copper} kW	P_{beam} kW	P_{total} kW
1	1	0.0744	0.0729	10.45	0.1807	-90	0.000	2.5	3.1246	0	3.1246
2	2	0.0771	0.0741	10.55	0.277	-50	0.178	2.678	7.2729	1.78	9.0529
3	3	0.0804	0.0767	10.994	0.2994	-50	0.192	2.871	8.1536	1.92	10.074
4	4	0.0842	0.0795	11.15	0.3336	-50	0.214	3.085	9.9811	2.14	12.121
5	5	0.0882	0.0825	15.64	0.3877	-50	0.249	3.334	9.6107	2.49	12.101
6	5	0.0882	0.0861	16.96	0.459	-45	0.325	3.659	12.422	3.25	15.672
7	8	0.1015	0.0905	14.38	0.5929	-45	0.419	4.078	24.446	4.19	28.636
8	8	0.1015	0.0955	17.16	0.6061	-40	0.464	4.542	21.408	4.64	26.048
9	8	0.1015	0.1008	18.62	0.6387	-35	0.523	5.065	21.909	5.23	27.139
10	11	0.116	0.1064	17.78	0.6983	-33	0.586	5.651	27.425	5.86	33.285
11	11	0.116	0.1121	19.77	0.7412	-33	0.622	6.273	27.788	6.22	34.008
12	11	0.116	0.1181	20.31	0.8216	-33	0.689	6.962	33.236	6.89	40.126
13	14	0.1316	0.1244	20.88	0.9425	-33	0.790	7.752	42.543	7.9	50.443
14	14	0.1316	0.1308	22.12	0.9071	-33	0.761	8.513	37.198	7.61	44.808
15	16	0.1422	0.1368	22.59	0.94	-33	0.788	9.301	39.115	7.88	46.995
16	16	0.1422	0.1426	23.29	1.0172	-40	0.779	10.081	44.427	7.79	52.217
								Total :	370.06	75.79	445.85

* from “Power tables for room temperature part of HINS”, G. Romanov, Dec 29, 2008. (Assumes 10 ma proton beam for beam power calculation).

Table 3. Superconducting Spoke Cavity Power Requirements**

1			Cavity voltage (kV)	Beam power (kW) for 25 mA	phase (deg)
18	SSR-1	17	1168.96269	25.30878465	-30
19		18	1240.16921	26.85045103	-30
20		19	1300.11845	28.14839015	-30
21		20	1350.24307	29.23362001	-30
22		21	1388.20499	30.05551969	-30
23		22	1417.65869	30.693211	-30
24		23	1438.62264	31.14709383	-30
25		24	1454.30679	31.48666564	-30
26		25	1464.28768	31.70275824	-30
27		26	1471.59134	31.86088712	-30
28		27	1472.14355	31.87284282	-30
29		28	1472.62197	31.88320092	-30
30		29	1472.34967	31.87730545	-30
31		30	1470.75775	31.84283937	-30
32		31	1467.38566	31.76983148	-30
33		32	1461.86191	31.65023878	-30
34		33	1453.87773	31.47737622	-30
35		34	1448.63582	27.74298552	-40

** from “Ostroumov_energy_Nov_2006-revision-Feb_07.xls”, Peter Ostroumov, February 2007. (Assumes 25 ma proton beam for beam power calculation).

Other Physical Factors

The production of x-rays from accelerated electrons is an inefficient process; at energies of concern here >90% of the electron beam power becomes heat in the x-ray producing target [1] [Appendix 1]. Since the superconducting state must be maintained for the SC cavities to operate at design accelerating fields, this is an important effect for estimating x-ray production by the SC cavities. Heat due to the electron beam power not converted to x-rays must be removed by the cryogenic system. That system is designed to remove only a few tens of watts, not 720 watts, from any cavity while maintaining it at superconducting temperature. Calculations in this paper take no credit for this limiting effect rendering them quite conservative. In addition, no credit is taken for x-ray shielding due to the ½ inch stainless steel wall of the cryomodule that houses the cavities. This represents another factor of two in safety margin.

Shielding Calculations

Based on the parameters described above and conservatively assuming that the entire average RF power is available to produce electrons of the specified energy, the electron current available for x-ray production from each cavity type is:

Copper 3-spoke	---	231 W / 0.11 MV = 2.1 mA
Copper 4-spoke	---	945 W / 0.25 MV = 3.8 mA
SC β=0.2 cavity	---	720 W / 0.75 MV = 1.0 mA

The corresponding absorbed dose rates D for x-rays at one meter from an x-ray producing target are obtained from graph E.1 in NCRP Report No.51.

For copper 3-spoke cavity

At 0° D = <0.5 (rad $m^{2)}$ / (min mA) x 2.1 mA = ~1 rad m^2/min

At 90° D = <1 (rad $m^{2)}$ / (min mA) x 2.1 mA = 2.1 rad m^2/min

For copper 4-spoke cavity

At 0° D = <0.5 (rad $m^{2)}$ / (min mA) x 3.8 mA = ~ 1.9 rad m^2/min

At 90° D = 1 (rad $m^{2)}$ / (min mA) x 3.8 mA = 3.8 rad m^2/min

For SC β=0.2 cavity

At 0° D = 8 (rad $m^{2)}$ / (min mA) x 0.67 mA = 5.4 rad m^2/min

At 90° D = 20 (rad $m^{2)}$ / (min mA) x 0.67 mA = 13.4 rad m^2/min

Following Table E.3 in NCRP 51, the dose rates at 0° and 90° may be multiplied by factors of 0.7 and 0.5 respectively for copper/iron production target materials. Taking the most conservative factor, 0.7, yields the most demanding case.

SC β=0.2 cavity at 90° D = 6.7 rad m^2/min

The shielding calculations that follow use this value.

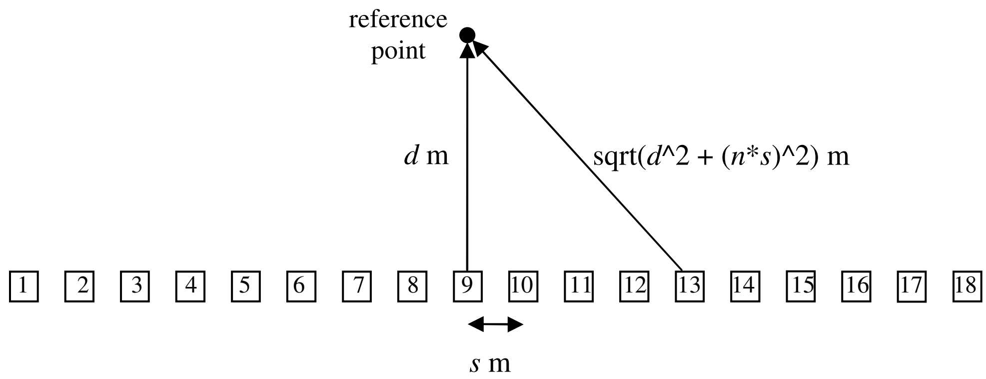


Figure 1. Superconducting Cavity Layout Geometry

This value represents the dose rate for a single point source. In the linac, there are 18 SC cavities distributed in two cryomodules with a typical cavity-to-cavity spacing of 0.75 meters. Figure 1 shows the configuration. The total potential dose at a point transverse to the line of cavities is the sum of that from each cavity with the respective distance factor taken into account. At the center of a line of $2k+1$ cavities spaced with a separation s meters, the dose at a radial distance d meters would be:

$$\frac{D_{total}}{d_{effective}^{2}} = 6.7 \cdot \left(\frac{-1}{d^2} + 2 \cdot \sum_{n=0}^{k} \frac{1}{d^2 + (n \cdot s)^2} \right) \text{ rad/min}$$

In the region of the SC cavities, the ceiling height of the enclosure is to be 10.5 feet. In that case, the building crane height limits the roof thickness to three feet. With a cavity centerline height of 50.6 inches, the distance to the top of the roof is 111.4 inches or 2.83 meters. This is the pertinent reference point for calculating potential dose from the cavities. The distances from the cavities to the enclosure sidewalls are larger and the sidewalls offer the possibility of greater shielding thickness if required.

Using d=2.8 m, s=0.75 m and conservatively taking the summation over k=9, the quantity $D_{total} / d_{effective}^2$ is found to be 7.5 rad/min. This is conservative in the sense that radiation from cavities upstream or downstream of the reference point 'sees' effectively increased shielding due to the angle of transit; for any reasonable shielding thickness, this effect dominates even over the $1/d^2$ transmission effect.

The shielding necessary to limit the dose rate to 1 mr/hr (H = 1) is calculated using NCRP 51 equation 4-3. Assume T = 1 and find:

$B \leq 1.67E\text{-}5 * H * (d_{effective}^2 / D_{total}) * (1/T) = 1.67E\text{-}5 * 1 * (1/7.5) = 2.2E\text{-}6$

The number of tenth-value layers (TVL) required to achieve this attenuation is n, where n = log(1/B) = 5.65

Figure E.12 in NCRP Report 51 gives the shielding dose equivalent tenth-value layer thickness for x-rays in concrete as a function of primary electron beam energy. For a 0.75 MeV electron beam, the first tenth-value layer is ~7 inches and subsequent layers are each ~5 inches. A concrete roof thickness of 36 inches therefore presents a shielding thickness of 1 + 29/5 = 6.8 TVLs. This is one full TVL greater than that required to limit the dose to <1 mr/hr on the enclosure roof for the worst case assumptions taken here.

Conclusion

Conservative calculations show that the HINS linac enclosure, if constructed with concrete walls and roof at least three feet thick, will provide adequate shielding to limit doses outside the enclosure due to RF cavity-produced x-rays to less than 0.1 mr/hr in the worst case.

References

1. Evans, Robley D., “The Atomic Nucleus”, McGraw-Hill, 1955, pp. 609-610.

Appendix 1. From "The Atomic Nucleus", Robley D. Evans

with Webber notations

THE ATOMIC NUCLEUS

Robley D. Evans, Ph.D.

PROFESSOR OF PHYSICS

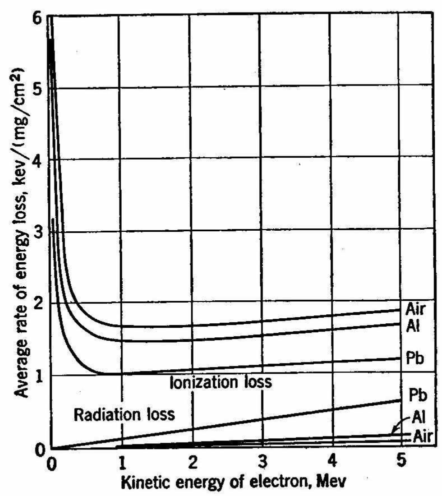
MASSACHUSETTS INSTITUTE OF TECHNOLOGY

New York Toronto London

McGRAW-HILL BOOK COMPANY, INC.

1955

The actual path of an electron while passing through an absorbing foil is not straight. Because of the effects of multiple scattering, the actual path length is always greater than the foil thickness traversed. The ratio of the actual path length to the superficial thickness of absorber traversed increases with Z (Chap. 21, Sec. 1). In the case of electrons (but not heavy particles), the effect of scattering almost exactly balances the decrease of dT/dw with increasing Z. Therefore, if distance is measured in terms of superficial thickness of absorber traversed, say, in milligrams per square centimeter, the ionization losses for positrons and



Note: this discussion assumes thin targets

Fig. 2.1 Mass-absorption energy losses for electrons in air, Al, and Pb. The upper three curves are $(dT/dw)_{\text{ion}}$, based on Eq. (2.26) of Chap. 18, with $dw = \rho\, ds$, and $I_{\text{air}} = 86$ ev, $I_{\text{Al}} = 165$ ev, $I_{\text{Pb}} = 750$ ev. The three lower curves show, on the same scales, the average energy loss due to bremsstrahlung $(dT/dw)_{\text{rad}}$ as obtained from Eq. (1.9), with $dw = \rho\, ds$. All curves refer to energy losses along the actual path traversed by the electron.

negatrons become nearly independent of the nature of the absorbing material. It is therefore common in reporting experimental work to use milligrams per square centimeter, or a similar unit, as the measure of absorber thickness.

c. Ratio of Radiative and Ionization Losses. Ionization losses per unit path length vary roughly as $1/\beta^2$ and so are largest for slow particles. On the other hand, radiative losses increase with increasing energy, Eq. (1.9). At high energies, $T \gg Mc^2$ in general, or $T \gg m_0c^2$ for electrons, the radiative losses become comparable with the ionization losses.

The ratio of the radiative to the ionization losses, for any particle of rest mass M_0, and high velocity $\beta \simeq 1$, is obtainable from the quotient of Eq. (1.9) and Eq. (2.26) of Chap. 18. With $137\sigma_0$ generalized to

$(e^2/M_0c^2)^2$, the ratio becomes approximately (B55)

$$\frac{(dT/ds)_{\text{rad}}}{(dT/ds)_{\text{ion}}} \simeq Z\left(\frac{m_0}{M_0}\right)^2\left(\frac{T}{1{,}600m_0c^2}\right) \tag{2.8}$$

The factor 1,600 holds for electrons ($M_0 = m_0$) but should be reduced to about 1,000 for mesons ($M_0 \sim 200m_0$). Thus we see that, for electrons, the radiative and ionization losses are equal for $T = 20m_0c^2 = 10$ Mev in Pb (and for $T \sim 100$ Mev in water or air).

The numerical values of σ_{rad} are such that *for electrons at* 10 *Mev the radiative and ionization losses are each equal to about* 1.6 *Mev per millimeter of* Pb, or a total of 3.2 Mev per millimeter of Pb for both. This makes a very convenient rule of thumb for estimating high-energy radiative losses (which increase approximately with NZ^2 and T) and ionization losses (which increase with NZ but are nearly independent of T).

So for example
with 3 MeV electrons on iron
$Z = 26$

$$\frac{\left(\frac{dT}{ds}\right)_{RAD}}{\left(\frac{dT}{ds}\right)_{ION}} = 26\left(\frac{1}{1}\right)^2\left(\frac{T = 3\text{ MeV}}{1600(\frac{1}{2}\text{ MeV})}\right)$$

$$= \frac{26 \cdot 3}{1600/2} \simeq \frac{78}{800} \simeq 10\%$$

So at 3 MeV only 10% of electron energy is converted to photons, 90% goes to ionization and therefore to heat in target

For thick targets (series of thin targets w/ ever decreasing electron energy) photon yield is lower yet.